

Differentiation of delta and open marine deposits based on an integrated ichnological and sedimentological analysis of the Late Triassic Nayband Formation, Tabas Block, Central Iran

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Abstract

Background The palaeoenvironmental significance of trace fossil assemblages in the shallow marine deposits of the Late Triassic Nayband Formation of the Tabas Block, Central Iran has been assessed for the first time. The siliciclastic successions of the Nayband Formation, are highly bioturbated and allow relationships between changes in ichnoassemblages within a depositional system to be documented and placed in a palaeoenvironmental framework. **Purpose** The main purposes of this paper are: (1) to describe and illustrate the trace fossils assemblages of the Nayband Formation; (2) integration of ichnologic and sedimentologic data to evaluate different stress factors on the infaunal communities; and (3) to briefly discuss paleoenvironmental distribution of various trace fossil assemblages in order to differentiate between deltaic and non-deltaic shoreface successions. **Methods** The Upper Triassic Nayband Formation has been studied and measured in one section, where the Nayband Formation is well accessible and continuously exposed. This section was logged and evaluated using physical

sedimentology and ichnology in order to establish a basis for the interpretation of sedimentary processes (facies) and depositional systems. In this study, trace fossils (diversity, abundances, and ethologies) and the spatial arrangement of sedimentary structures are used to further refining the interpretation of environmental parameters such as hydrodynamic energy, water turbidity, substrate properties, food supply, temperature, oxygenation, salinity, and sedimentation rates.

Results Based on facies characteristics and stratal geometries, the siliciclastic succession is divided into two facies associations, fluvial-dominated delta (FA), and open marine (FB). Twenty-eight ichnogenera have been identified in delta and open marine successions: The assemblage is dominated by *Rhizocorallium*, *Thalassinoides*, *Ophiomorpha*, *Helminthopsis*, *Palaeophycus* and *Skolithos*. Their distribution is clearly linked with lithofacies and depositional environments.

Conclusion High rates of fluvial discharge, high water turbidity, seasonally high rates of deposition and phyto-detrital pulses in river-dominated deltas may cause marked variations in the temperature, oxygenation and salinity of the fluvial-dominated delta successions. All of these factors in combination lead to impoverishment in trace diversity and reduction in burrow size but to rapid colonization of the substrate by single-layer colonizers of opportunistic deposit feeders. Low ichnodiversity, low bioturbation intensities with highly bioturbated clusters shown by single colonization events by opportunistic, simple feeding strategies of trophic generalists and a paucity of suspension-feeding structures elements represent a “stressed”, non-archetypal *Cruziana* ichnofacies. The changes of behavioural complexity and the tiering profiles in the offshore-shoreface complex of the Nayband Formation when compared with the river-dominated delta

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successions represent the transition from epifaunal life habits with simple tiering structures to infaunal life habits with complex tiering pattern. The occurrence of diverse trace fossil suites attributable to the *Zoophycos* ichnofacies, the archetypal *Cruziana* ichnofacies and the *Skolithos* ichnofacies in wave-dominated shoreface-offshore complex point to stress-free environmental conditions in open waters due to persistent wave agitation, and hence, a wide colonization window.

Keywords Nayband formation · Fluvial-dominated delta · Open marine · Archetypal ichnofacies · Iran

Resumen

Antecedentes Se ha evaluado por primera vez la importancia paleoambiental de las asociaciones de fósiles en los depósitos marinos poco profundos de la Formación Nayband del bloque de Tabas, Irán central, datada del Triásico tardío. Las sucesiones siliciclasticas de la Formación Nayband están altamente bioturbadas y permiten relacionar los cambios en asambleas de trazas fósiles dentro de un sistema deposicional para ser documentados y colocados en un marco paleoambiental.

Objetivos Los principales propósitos de este trabajo son: (1) describir e ilustrar las asociaciones de trazas fósiles de la Formación Nayband; (2) integración de datos icnológicos y sedimentológicos para evaluar diferentes factores de estrés en las comunidades endobentónicas; y (3) discutir brevemente la distribución paleoambiental de varios conjuntos de trazas fósiles con el fin de diferenciar entre las sucesiones shoreface deltaicas y no-deltaicas.

Métodos La Formación Nayband del Triásico Superior se ha estudiado y medido en una sección, donde la secuencia es bien accesible y permanentemente expuesta. Esta sección se registró y evaluó utilizando sedimentología física e icnología con el fin de establecer una base para la interpretación de los procesos sedimentarios (facies) y sistemas de deposición. En este estudio se usan trazas fósiles (diversidad, abundancias y etologías) y la disposición espacial de estructuras sedimentarias para refinar aún más la interpretación de parámetros ambientales tales como energía hidrodinámica, turbidez del agua, propiedades del sustrato, suministro de alimentos, temperatura, oxigenación, salinidad, y tasas de sedimentación.

Resultados A partir de las características faciales y geometrías estratales, la sucesión siliciclastica se divide en dos asociaciones de facies, delta fluvial (FA) y mar abierto (FB). Veintiocho icnógenos han sido identificados en sucesiones de delta y marinas abiertas: El conjunto está dominado por *Rhizocorallium*, *Thalassinoides*, *Ophiomorpha*, *Helminthopsis*, *Palaeophycus* y *Skolithos*. Su distribución está claramente relacionada con las litofacies y los ambientes de deposición.

Conclusiones Las altas tasas de descarga fluvial, alta turbidez del agua, estacionalmente altas tasas de deposición y pulsos de fitodetritos en deltas con influencia fluvial pueden causar marcadas variaciones en la temperatura, la oxigenación y la salinidad. Todos estos factores en combinación llevan al empobrecimiento en la diversidad de trazas y reducción en el tamaño de las madrigueras, así como a una rápida colonización del sustrato por los animales depositívoros oportunistas colonizadores de una sola capa. Icnodiversidad baja, bajas intensidades de bioturbación con concentraciones altamente bioturbadas mostradas por eventos de colonización individuales mediante estrategias oportunistas y simples de alimentación de los generalistas tróficos y una escasez de estructuras de alimentación suspensívora representan icnofacies de *Cruziana* “estresantes” no arquetípicas. Los cambios de la complejidad del comportamiento y los perfiles de organización en niveles del complejo en alta mar-cara de playa de la Formación Nayband cuando se compara con las sucesiones de delta con influencia fluvial representan la transición de los hábitos de vida epifaunales con estructuras de organización en niveles sencillos para hábitos de vida infaunales con el patrón complejo de organización en niveles. La ocurrencia de suites de trazas fósiles diversas atribuible a la icnofacies de *Zoophycos*, a la icnofacies de *Cruziana* arquetípica y a la icnofacies de *Skolithos* en un complejo cara de playa-costa afuera dominada por la influencia de las olas apuntan para condiciones ambientales libres de estrés en aguas abiertas debido a la agitación de ola persistente, y por lo tanto, creando una amplia ventana para la colonización.

Palabras clave Formación de Nayband · Delta con influencia fluvial · Mar abierto · Icnofacies arquetípicas · Irán

1 Introduction

The trace fossil distribution and composition of ichnoassemblages can impart considerable information regarding the palaeoecology, the depositional environment and environmental parameters (e.g. Gingras et al. 1998; 2011; Bann and Fielding 2004; Buatois and Mángano 2011; Bayet-Goll and Neto De Carvalho 2015; Bayet-Goll et al. 2015a, 2016a). An integrated approach combining ichnological and sedimentological features has significantly enhanced the palaeoenvironmental interpretations of the Late Triassic successions from Iran (see Fürsich et al. 2007; Fig. 1). In this paper, trace fossils and the spatial arrangement of sedimentary structures are used to further refining the interpretation of environmental parameters such as hydrodynamic energy, water turbidity, substrate

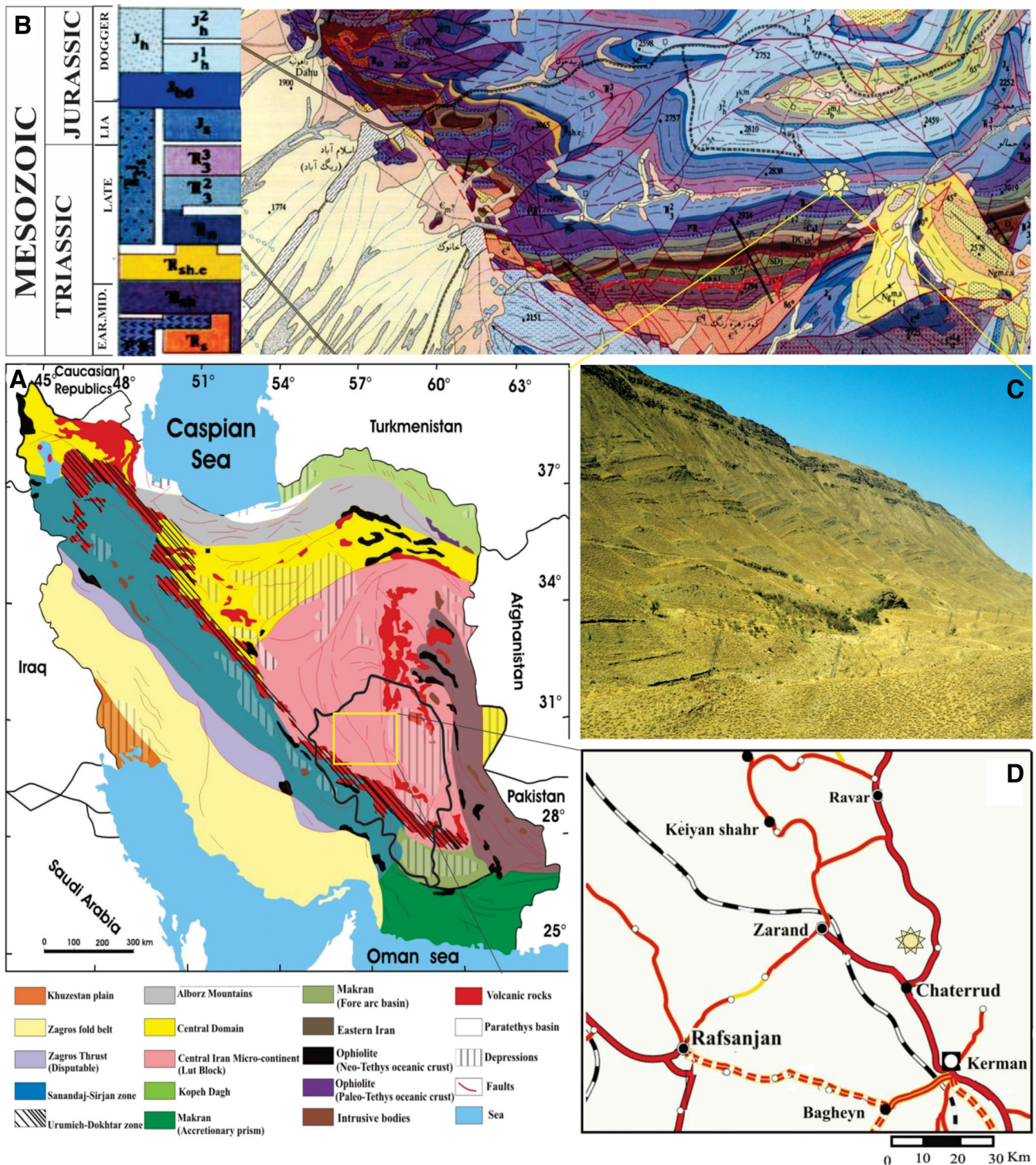


Fig. 1 a Geological map of Iran with its structural provinces after Nezafti (2006). b Geological map of the northern part of Kerman Province in the Zarand area (Vahdati-Daneshmand, 1995). c Panoramic view of the upper part of the lower member (Gelkan

and the upper member (Howz-e-Sheikh) of the Nayband Formation in the study area. d Position of the study area at 35 km E of the city of Zarand

properties, food supply, temperature, oxygenation, salinity, and sedimentation rates. For this purpose, the Late Triassic ichnotaxa from the Nayband Formation are documented

and the facies implications of various trace fossil assemblages are portrayed to differentiate between deltaic and non-deltaic shoreface successions.

2 Geological setting

The study area is located in the central part of the Central-East Iranian Microcontinent (CEIM). The Tabas Basin is an intra-continental depression and a part of the CEIM (Aghanabati 2004) that has experienced a complex structural history (Fig. 1). From the Precambrian to the Permian, central Iran was part of northwestern Gondwana (Alavi 1991; Stampfli et al. 1991; Fürsich et al. 2009). During Permian times, the CEIM was detached from Gondwana and moved towards Eurasia. This collision caused the closure of the Palaeotethys Ocean and a series of events related to tectonic uplift, magmatism, and metamorphism traditionally termed as the Early Cimmerian orogeny (Aghanabati 2004; Wilmsen et al. 2009). This Middle-Late Triassic tectonic phase resulted in the formation of high-reliefs that served as a source for the thick siliciclastic deposits of the Nayband and Shemshak formations (Fürsich et al. 2005, 2009; Wilmsen et al. 2009).

The Late Triassic (Norian-Rhaetian) Nayband Formation is distributed over a large area in central and eastern Iran (Seyed-Emami 2003). Four members have been recognized at the type locality of the formation (e.g., Fürsich et al. 2005), which are, from the base to the top: (1) Gelkan Member, (2) Bidestan Member, (3) Howz-e-Sheikh Member and (4) Howz-e-Khan Member. Siliciclastic sediments (silts, sandstones) dominate in the Gelkan and Howz-e-Sheikh members, whereas carbonates are a characteristic feature of the Bidestan and Howz-e-Khan members (Fürsich et al. 2005). The Nayband Formation contains a rich benthic macrofauna, including bivalves, corals, diverse groups of sponges, subordinate elements of brachiopods, echinoderms and gastropods (Fürsich et al. 2005). Based on these studies, the age of Nayband Formation is Late Triassic (Norian to Rhaetian; Nützel et al. 2003; Cirilli et al. 2005; Fürsich et al. 2005).

The Nayband Formation covers a large area near, the city of Zarand, northern Kerman Province. In the study area, the formation can be subdivided into: (1) the Gelkan Member, composed of thick layers of sandstones and shales and (2) the Howz-e-Sheikh Member, consisting of shales and sandstone, dark-green silty calcareous shales, siltstone and limestone. The Bidestan and Howz-e-Khan members are not recorded. This formation unconformably overlies shallow-water carbonate platform sediments of Middle Triassic Sotori Formation and is followed by the Early Jurassic Ab-e-Haji Formation.

3 Materials and methods

A well accessible and continuously exposed section (coordinates N 30°44'12", E 56°51'4") of the Nayband Formation was studied, measured and sampled in the Zarand

area (Fig. 2). Sedimentological data used to interpret depositional facies include: lithology, faunal content, bed geometry and contacts, bed thickness, physical sedimentary structures, bounding surfaces, lateral/vertical variations in facies and thicknesses and the identification of important stratigraphic surfaces. The ichnological study is based on the concept of ichnofacies, which are recurring ethological groupings of traces or trace fossils (MacEachern et al. 2007a; MacEachern and Bann 2008; Buatois and Mángano 2011). Ichnofacies approach was adopted to frame the trace-fossil information, taking into account ichnotaxa identification (Seilacher 1964, 2007; Häntzschel 1975; Uchman 1995, 1998; Monaco and Checconi 2008), ethological and trophic types (cf. Bromley 1996), population strategies, ichnodiversity, relationships among trace fossils, physical sedimentary structures, and bedding types (e.g., Monaco and Caracuel 2007; Monaco et al. 2009). Bioturbation intensities were assigned a Bioturbation Index (BI) value (cf. Taylor and Goldring 1993), with 0 defining the absence of bioturbation and 6 reflecting complete bioturbation. This information provided a basis for the interpretation of sedimentary processes (facies) and depositional systems (facies associations) (Bayet-Goll et al. 2015a, 2016a, b).

4 Brief description of ichnotaxa

Data in Table 1 provide a systematic description of the trace fossils identified in the Nayband Formation. Trace fossils were mainly studied in the field and ichnotaxonomic analysis was complemented with photographs and collected specimens. The repository of collected material is the Department of Geology, Ferdowsi University of Mashhad and Institute for Advanced Studies in Basic Sciences (IASBS), Zanjan. Trace fossils were studied in transverse and longitudinal section considering their three-dimensional morphology, structure, and ornamentation of the outer surface (Figs. 3, 4). Ichnotaxa are arranged alphabetically, and their analysis includes a brief discussion about ichnotaxonomy, environmental distribution, and probable ethology of the tracemaker.

5 Sedimentary facies and trace fossil distribution

A facies analysis of the Nayband Formation, emphasizing the role of ichnological data, was presented by Bayet-Goll (2016). This combined lithofacies/ichnofacies scheme is extended and further details of the ichnological and sedimentological data are given here. The collected data have been presented on one stratigraphic section (Fig. 2). The facies scheme comprises two facies associations. Facies

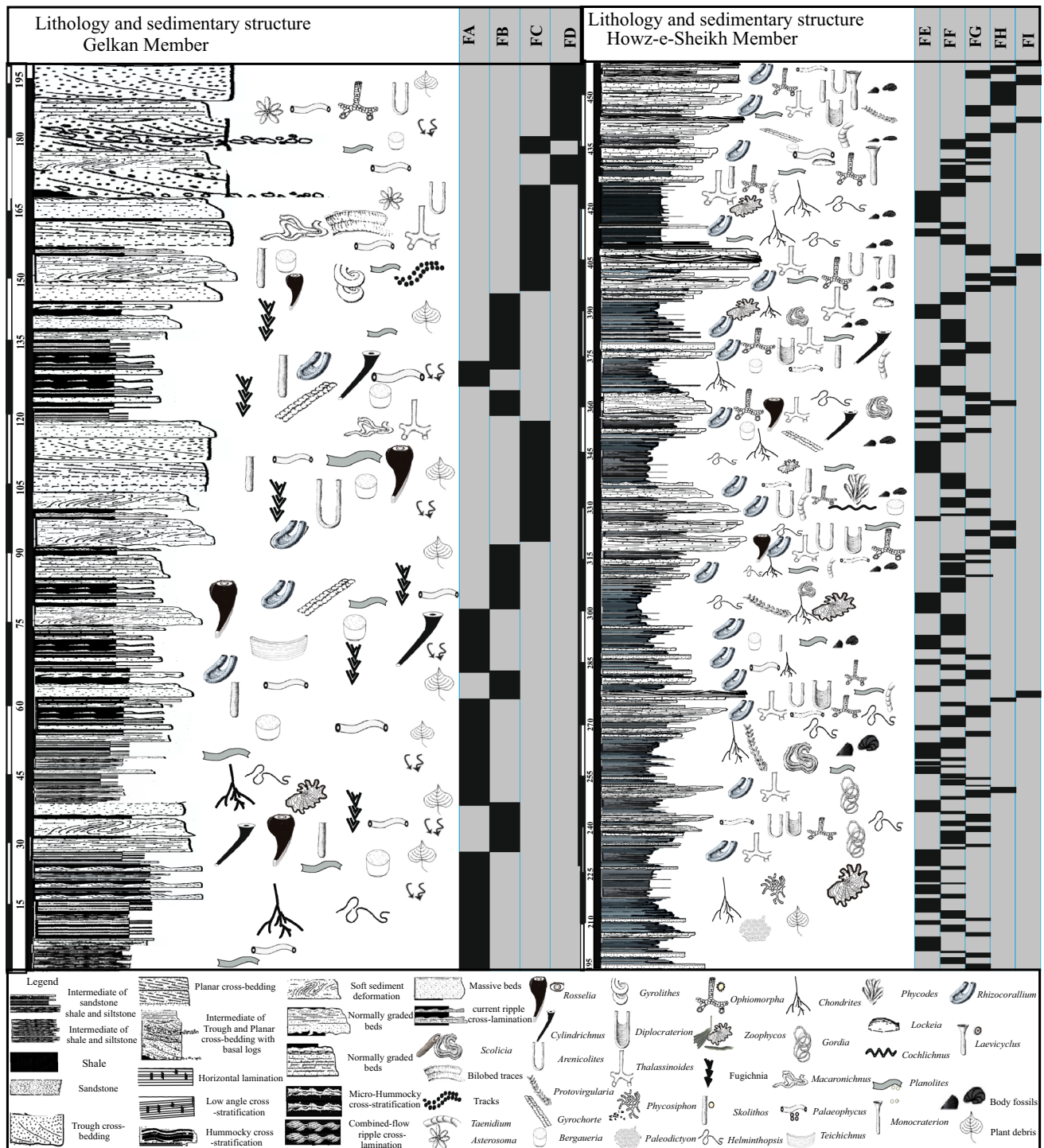


Fig. 2 Stratigraphic sections measured at Zarand showing the sedimentological-ichnological characteristics and interpretation of the depositional environments of the Nayband Formation. *Left* River-

dominated delta succession. *Right* The open-marine facies association (some used *symbols* for trace fossils after Seilacher 2007; MacEachern et al. 2007a; Bann et al. 2008)

Association A consists of four facies and records deposition in a fluvial-dominated delta. Facies Association B contains five facies and records a complete spectrum of

shallow-marine deposits, ranging from shelf through offshore and offshore transition to shoreface and foreshore environments.

Table 1 Ichnotaxa identified in the Nayband Formation. Information includes description, environmental distribution, ethology, and probable trace makers

Ichnotaxon	Diagnostic character	Probable trace makers and ethologic types	Environmental distribution in Nayband formation
<i>Arenicolites</i> isp.	Vertical U-tubes preserved in full relief, numerous paired tubes, without spreiten	Dwelling burrows of suspension-feeders (domichnion), annelids (Bromley 1996)	In both delta and open marine deposits; proximal mouth bar, distributary channel fills, offshore transition, lower shoreface
<i>Asterosoma</i> cf. <i>radiciforme</i> (Von Otto 1854)	Cylindrical and flattened tunnels, radial or star-like pattern with tapering ends; radiating outward and upward from a common point at the base	Deposit-feeding activity of worms/annelids and decapod crustaceans (Neto de Carvalho and Rodrigues 2007)	In delta deposits; very rare; distal mouth bar, proximal mouth bar
<i>Bergaueria</i> isp.	Hypichnial mound with hemispherical termination, oval in outline, rounded or flattened base	Cubichnial by suspension feeders of acerianthid or actinarian anemones (Fillion and Pickerill 1990)	In both delta and open marine deposits
<i>B. hemispherica</i> (Crimes et al. 1977)	Hypichnial mound oriented perpendicular to bedding, oval in outline with more flattened underneath	Resting (cubichnia) or dwelling (domichnia) structures (Pemberton et al. 2001)	In delta deposits; very rare; proximal mouth bar, D distributary channel fills
<i>B. perata</i> (Prantl 1945)	Shallow cylindrical burrows with hemispherical lower end bearing a small central depression	Resting traces	In open marine deposits; very rare in offshore transition facies
<i>Cochlichnus</i> isp.	Sinuous traces preserved as convex epireliefs with uniform curves with high sinuosity	Grazing trail (pascichnion) to locomotion trail (repichnion) of a worm-like organism (Bromley 1990)	In open marine deposits; very rare in distal lower shoreface facies
<i>Chondrites</i> isp.	Endichnial burrow system consisting of tree-like branching burrows, straight to gently curved	Feeding system (fodinichnion) of unknown trace-makers related to infaunal deposit-feeders (Bromley 1990)	In both delta and open marine deposits, prodelta, shelf, lower offshore
<i>C. intricatus</i> (Brongniart 1828)	Tree-like branching burrows, with tunnels branching out at sharp angles	Infaunal deposit-feeders; interpreted as a fodinichnion (Bromley 1990)	In open marine deposits; very rare in lower offshore
<i>Cylindrichnus</i> isp.	Straight to slightly curved burrows, concentrically lined cylinders with distinct mud lining, tapering over their length	Dwelling structure of filter feeding organisms such as worms/annelids (Goldring 1996)	In both delta and open marine deposits; distal mouth bar, proximal mouth bar, offshore transition
<i>Diplocraterion</i> isp.	Dumb-bell shaped trace consisting of two circular sections of vertical tubes joined by laminae of reworked material (i.e. spreite)	Dwelling burrow of suspension-feeding organisms (Fillion and Pickerill 1990)	In open marine deposits; very rare in offshore transition, lower shoreface
<i>Helminthopsis</i> isp.	Unbranched, curved, cylindrical to subcylindrical burrows; smooth, winding to irregularly meandering	Grazing trails produced by deposit-feeder organisms, probably polychaete annelids (Bromley 1996)	In both delta and open marine deposits; prodelta, shelf, lower offshore, offshore transition
<i>H. abeli</i> (Książkiewicz 1977)	Winding to irregularly meandering; with open meanders and horseshoe-like turns	Grazing trails produced by deposit-feeders	In open marine deposits; very rare in lower offshore
<i>H. hieroglyphica</i> (Maillard, 1887)	Irregularly meandering, horizontal, cylindrical, unbranched burrows, with alternating winding more or less straight courses	Grazing trails produced by deposit-feeders	In open marine deposits; very rare in lower offshore
<i>Gyrochorte</i> isp.	Horizontal trails consisting of plaited ridges with biserially arranged long parallel ridges, transverse plaits separated by a median furrow	Fodinichnion of worm-like organism or mollusk moving obliquely through the sediment (Bromley 1996)	In both delta and open marine deposits; mouth bar, offshore transition, lower shoreface
<i>G. comosa</i> (Heer 1865)	Long, straight or curved burrows with backfill structures which are biserially arranged as plaited ridges with long parallel ridges	Fodinichnion of worm-like organism	In open marine deposits; in offshore transition

Table 1 continued

Ichnotaxon	Diagnostic character	Probable trace makers and ethologic types	Environmental distribution in Nayband formation
<i>Gordia marina</i> (Emmons 1844)	Curved, unbranched, winding to irregularly meandering burrows; with irregular courses and looped segments	Grazing trails produced by deposit-feeder organisms, probably polychaete annelids (Bromley 1996)	In open marine deposits; very rare, in shelf and lower offshore
<i>Gyrolithes</i> isp.	Full relief, endichnial, cylindrical burrows; corkscrew-shaped spiral, consisting of a single whorl	Domichnia trace produced by different kinds of crustaceans and polychaetes (Bromley 1996)	In delta deposits; very rare; proximal mouth bar
<i>Laevicyclus</i> isp.	Vertical, straight, simple, cylindrical structures, concentric around a central shaft, surrounded by circles and right angle to the bedding plane	Dwelling burrow of suspension-feeding organisms (Bromley 1990)	In open marine deposits; in distal lower shoreface, and proximal lower shoreface
<i>Lockeia</i> isp.	Convex hyporelief; small, bilaterally symmetrical, almond shaped, tapering at both ends	Resting traces of small burrowing bivalves, perhaps semi-sessile forms (Bromley 1996)	In open marine deposits; relatively rare, in distal lower shoreface
<i>Macaronichnus</i> isp.	Irregularly trails with open to tight meander bends, composed of a core surrounded by a mantle	Fodinichnion produced by vagile, deep deposit-feeding worms (Pemberton et al. 2001)	In delta deposits; very rare, proximal mouth bar
<i>Monocraterion</i> isp	Endichnial full burrow; vertical, conical structures; consists of central shaft surrounded by concentric laminae	The dwelling burrow of a suspension-feeding worm-like organism (Pemberton et al. 2001)	In open marine deposits; relatively rare, in Proximal lower shoreface
<i>M. tentaculatum</i> (Torell 1870)	Vertical, straight, concentrically laminated conical structures with mud lining along burrow wall of both tubes and funnels	The dwelling burrow of a suspension-feeder	In open marine deposits; relatively rare, in proximal lower shoreface
<i>Ophiomorpha</i> isp.	Endichnial burrows, vertical, long straight shafts, cylindrical structures packed with pellets	Dwelling structure of a suspension-feeder produced by shrimps comparable to callianassids (Frey et al. 1978)	Delta and open marine deposits; distributary channel fills, offshore transition, lower shoreface
<i>O. nodosa</i> (Lundgren 1891)	Endichnial, horizontal, vertical, sub-vertical, branched or unbranched burrow, with smooth interior walls and distinct nodose exterior surfaces	Dwelling structure of a suspension-feeder	In open marine deposits; very rare in offshore transition and distal lower shoreface
<i>O. irregular</i> (Frey et al. 1978)	Branched or unbranched burrows, with vertical and horizontal components, walls composed of dense, irregularly distributed ovoid pellets	Dwelling structure of a suspension-feeder (domichnion)	In open marine deposits; relatively rare in offshore transition and Distal lower shoreface
<i>Palaeophycus</i> isp.	Straight to slightly curved, smooth-walled, horizontal, endichnial, cylindrical burrows showing mud linings	Temporary or permanent dwelling structure of a suspension feeder or predator (Pemberton and Frey 1982)	In both of delta and open marine deposits; distributary channel fills, offshore, lower shoreface
<i>P. tubularis</i> (Hall 1847)	Straight to slightly curved cylindrical to subcylindrical burrows; thinly walled, unbranched, with discrete lining and without ornamentation	Temporary or permanent dwelling structure	In both of delta and open marine deposits; prodelta, offshore transition, and distal lower shoreface
<i>P. cf annulatus</i> (Badve, 1987)	Straight to slightly curved, cylindrical, unbranched, distinctly lined, encircled by thin ring-like structures or annulations	Temporary or permanent dwelling structure	In open marine deposits; very rare, in offshore transition and distal lower shoreface
<i>P. heberti</i> (Saporta 1872)	Straight to slightly curved, horizontal, endichnial, cylindrical burrows, thickly lined, unornamented	Temporary or permanent dwelling structure	In open marine deposits; in offshore transition and distal lower shoreface
<i>P. striatus</i>	Straight to slightly curved, horizontal, lined and ornamented by longitudinal parallel grooves	Temporary or permanent dwelling structure	In open marine deposits; very rare in distal lower shoreface
<i>Paleodictyon</i> isp.	Network of hexagonal polygons, equidimensional to elongate horizontal meshes	Agrichnia and/traps meiobenthic organisms (Uchman 1995)	In open marine deposits; very rare in shelf

Table 1 continued

Ichnotaxon	Diagnostic character	Probable trace makers and ethologic types	Environmental distribution in Nayband formation
<i>Phycodes</i> isp.	composed of loosely packed bundle of tunnels; irregularly branched, radiating from the same point, spread in a palmate to flabellate fashion	Fodinichnia, produced by sediment-feeding vermiform annelid (Fillion and Pickerill 1990)	In open marine deposits; very rare in distal lower shoreface
<i>Phycosiphon</i> isp.	Small, narrow, sinuous to U-shaped tubes recurving as a series of lobes as protrusive spreiten-structures	Opportunistic deposit feeder (Wetzel and Bromley 1994)	In open marine deposits; very rare in shelf
<i>Planolites</i> isp.	Horizontal, long, cylindrical, smooth-walled, unlined, straight to gently curved, unbranched burrow	Fodinichnia/Pascichnia, product of vermiform deposit feeders (Pemberton and Frey 1982)	In both delta and open marine deposits
<i>P. beverleyensis</i> (Billings 1862)	Cylindrical to sub-cylindrical, smooth walled, unlined, straight to gently curved or sinuous, unbranched, horizontal structures	Worm-like mobile deposit feeder	In both delta and open marine deposits; mouth bar, offshore transition, lower shoreface
<i>Protovirgularia</i> isp.	Long, horizontal or subhorizontal trail, distinctly bilobed; with ribs arranged in chevron-shape	Combined activity of search for food and locomotion by bivalves and scaphopods (Seilacher and Seilacher 1994)	In open marine deposits; lower offshore, offshore transition, lower shoreface
<i>P. rugosa</i> (Miller and Dyer 1878)	Straight or curved ridges; triangular in cross-section, distinctly bilobed; covered with ribs arranged in chevron-shape	Combined activity of search for food and locomotion by bivalves and scaphopods (Seilacher and Seilacher 1994)	In open marine deposits; very rare in offshore transition
<i>Rhizocorallium</i> isp.	Simple, horizontal, straight to slightly sinuous, comparatively short U-shaped protrusive spreiten-burrows, with parallel limbs	Deposit-feeding crustaceans (Fürsich, 1975) or annelids (Pemberton et al. 2001)	In both delta and open marine deposits; mouth bar, offshore transition, distal/proximal lower shoreface
<i>R. jenense</i> (Zenker 1836)	Straight to slightly sinuous, short U-shaped protrusive or retrusive spreiten-burrows, horizontal or oblique to the bedding plane	Suspension-feeding structure with domichnial behaviour produced by scavenging organisms (Fürsich 1975)	In open marine deposits; in offshore transition, lower shoreface
<i>R. irregular</i> (Mayer 1954)	Horizontal, straight or slightly sinuous, U-shaped protrusive spreiten-burrows, parallel to bedding plane	Formed by deposit feeding organisms (Fürsich 1975)	In open marine deposits; in offshore transition, distal lower shoreface
<i>Rosselia</i> isp.	Isolated, vertical or subvertical funnel-shaped burrows with central tube filled with sandy sediment	Permanent dwelling burrows of filter feeding organisms or polychaete annelids (Fillion and Pickerill 1990)	In both delta and open marine deposits; proximal mouth bar, offshore transition
<i>Scolicia</i> isp.	Bilobed backfilled ribbon like traces, smooth winding or meandering burrows, divided by a semicircular axial furrow	Combined activity of search for food and locomotion of gastropods (Uchman 1995)	In open marine deposits; very rare in shelf
<i>Skolithos</i> isp.	Vertical, straight, simple, found in the bedding plane, mostly isolated cylinders; locally dense occurrences with more or less uniform diameter	Domichnion made by phoroids or annelids and suspension feeding polychaetes (Pemberton et al. 2001)	In both delta and open marine deposits
<i>Taenidium</i> isp.	Horizontal, straight to gently winding, unlined, meniscate burrows, menisci show unequal thickness, sparse packing and low curvature to arcuate	Back-filled feeding burrows (fodinichnia) of vagile vermiform animals (D'Alessandro and Bromley 1987)	In open marine deposits; very rare in offshore transition and distal lower shoreface
<i>T. cameronensis</i> (Brady 1947)	Horizontal to weakly inclined to bedding, unlined, unbranched, with meniscate backfill structures; menisci consisting of variable, chevron-shaped sediment packages	Back-filled feeding burrows (fodinichnia)	In open marine deposits; very rare in offshore transition
<i>Teichichnus</i> isp.	Vertical to inclined cylindrical burrows with retrusive spreite horizontal stacked circular U-shaped burrow	Combined feeding–dwelling activity of vermiform animals (Pemberton et al. 2001)	In delta deposits; relatively rare; in prodelta, distal mouth bar

Table 1 continued

Ichnotaxon	Diagnostic character	Probable trace makers and ethologic types	Environmental distribution in Nayband formation
<i>Thalassinoides horizontalis</i> (Myrow 1995)	Three-dimensional, unlined, large horizontal burrows, parallel to the bedding plane with Y/T-shaped branching	Produced by crustaceans, or other type of arthropods, as deposit feeders or fodinichnia/domichnia (Pemberton et al. 2001)	In both delta and open marine deposits; mouth bar, lower shoreface, offshore
<i>T. paradoxicus</i> (Rieth 1932)	Smooth, irregularly branched burrow systems consisting of a horizontal network connected to the surface by a more or less vertical shaft	Fodinichnia/domichnia	In both delta and open marine deposits; mouth bar, lower shoreface, offshore
<i>T. suevicus</i> (Rieth 1932)	Horizontal regularly branched burrow with T-shaped and Y-shaped bifurcations and swelling at the point of bifurcation with smooth surface and unornamented	Fodinichnia/domichnia	In open marine deposits; in distal lower shoreface and proximal lower shoreface
<i>Zoophycos</i> isp.	Endichnial, helicoidal trace, spreiten structures comprising numerous more or less U- or J-shaped protrusive burrows	Feeding system of unknown trace-makers related to infaunal deposit-feeders (fodinichnion, Bromley 1990)	In both delta and open marine deposits; mouth bar, shelf, lower offshore
Fugichnion	Sub-vertical, unlined, tortuous tubes, showing downwarping of strata in their central part	Representing escape structures	In delta deposits; distal mouth bar, proximal mouth bar
Bilobed traces	Bilobate, highly irregular to straight burrows in convex hyporelief; showing large and flat lobes, with slightly oblique scratch marks, a well-marked groove separating two lobes		In delta deposits; relatively rare; proximal mouth bar
Imprints of trackway	Series of irregular to parallel ridges, form ovoid; and preserved as hyporelief surface; trackway composed of two rows of imprints; oblique to track axis		In delta deposits; relatively rare; in proximal mouth bar

5.1 Facies association A: deltaic deposits

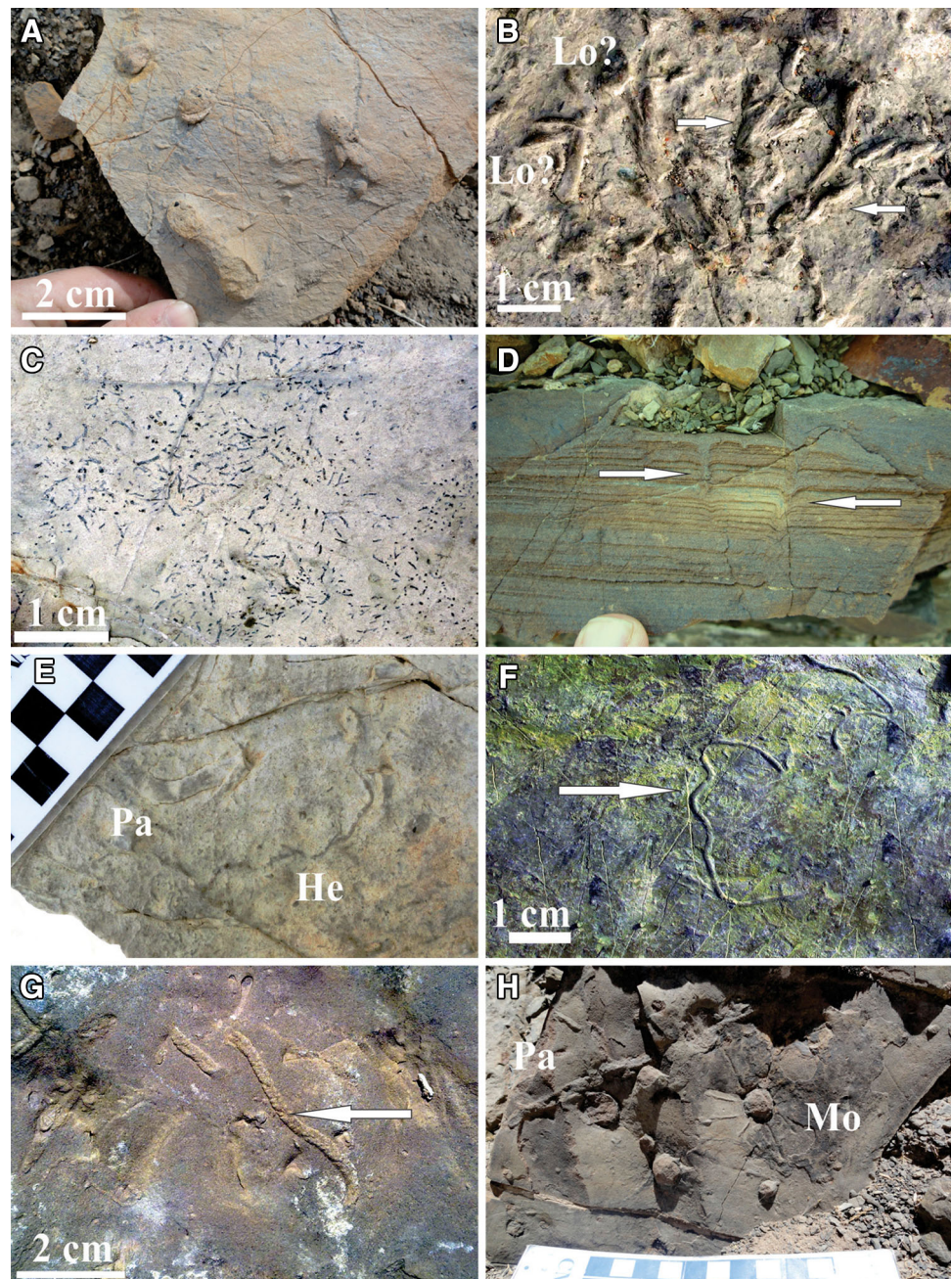
5.1.1 Facies A: prodelta

This facies is characterized by grey massive mudstone, with subordinate thin-bedded siltstones, silty sandstones and thin, very fine–fine-grained current-rippled and laminated sandstone (2–10 cm) (Fig. 5a) with organic plant material, synaeresis cracks and soft-sediment deformation structures. Centimetre- to decimetre-thick graded mudstones and silty sandstones with internal scour surfaces and lacking bioturbation are abundant.

This facies is commonly characterized by a low bioturbation intensity (B I 0–1), low ichnodiversity, small burrow diameters, absence of biodeformational structures and small depth of bioturbation, restricted to only a few centimetres. The main constituents of Facies A are simple, shallow-tiers representing simple pascichnia (grazing) and fodinichnia behaviours (*Planolites* isp., *Palaeophycus* isp., *P. tubularis*) and deep-tier endichnial fodinichnia (*Chondrites*). Shallow to mid-tier *Teichichnus* isp., *Zoophycos* isp., and *Helminthopsis* isp. constitute a subordinate suite.

Interpretation: Based on sedimentological features and stratigraphic relations with other facies, Facies A is interpreted to represent deposition within the prodelta of a river-influenced delta. The massive mudstones and siltstones indicate deposition by suspension fallout in a low-energy environment, whereas the ripple-laminated siltstone and sandstone intervals were deposited by weak traction currents. Generally, Facies A is characterized by heightened river-derived physico-chemical stresses (elevated sedimentation rates, hyperpycnal flows, salinity fluctuations, turbid waters, loading and dewatering) (e.g., MacEachern et al. 2005; Bhattacharya and MacEachern 2009; Bhattacharya et al. 2011). Moreover, normal/inversely graded beds and massive mudstones are interpreted to record hyperpycnal flows transporting mud turbidites (e.g., Bhattacharya and MacEachern 2009). The trace fossil suite represents a stressed distal expression of the *Cruziana* ichnofacies (MacEachern et al. 2007b). The depauperated *Cruziana* ichnofacies expressed persistent environmental fluctuations and a narrow colonization window (e.g., Bann and Fielding 2004; MacEachern et al. 2005, 2007b; Buatois et al. 2008, 2012; Bayet-Goll and Neto De Carvalho 2015).

Fig. 3 Photographs of ichnogenera from the middle member of the Nayband Formation. **a** Bedding-plane view with *Diplocraterion* isp. in cross-section. **b** *Asterosoma* cf. *radiciforme* (arrows) with *Lockeia* isp. (Lo?) **c** *Chondrites intricatus*. **d** Fugichnia within distal delta-front sandstones (arrows). **e** *Helminthopsis abeli* (He) and *Palaeophycus* isp. (Pa) on the lower surface of fine-grained sandstone. **f** *Helminthopsis hieroglyphica*; more or less straight courses or box-like hieroglyphic meanders with unknown vertical traces. **g** *Gyrochorte comosa*, showing biserially arranged plaited ridges. **h** Bedding-plane view of sandstone bed with *Monocraterion tentaculatum* (Mo); radiating burrows from an elevated central knob, with *Palaeophycus heberti* (Pa) and vertical dwelling burrows (?)



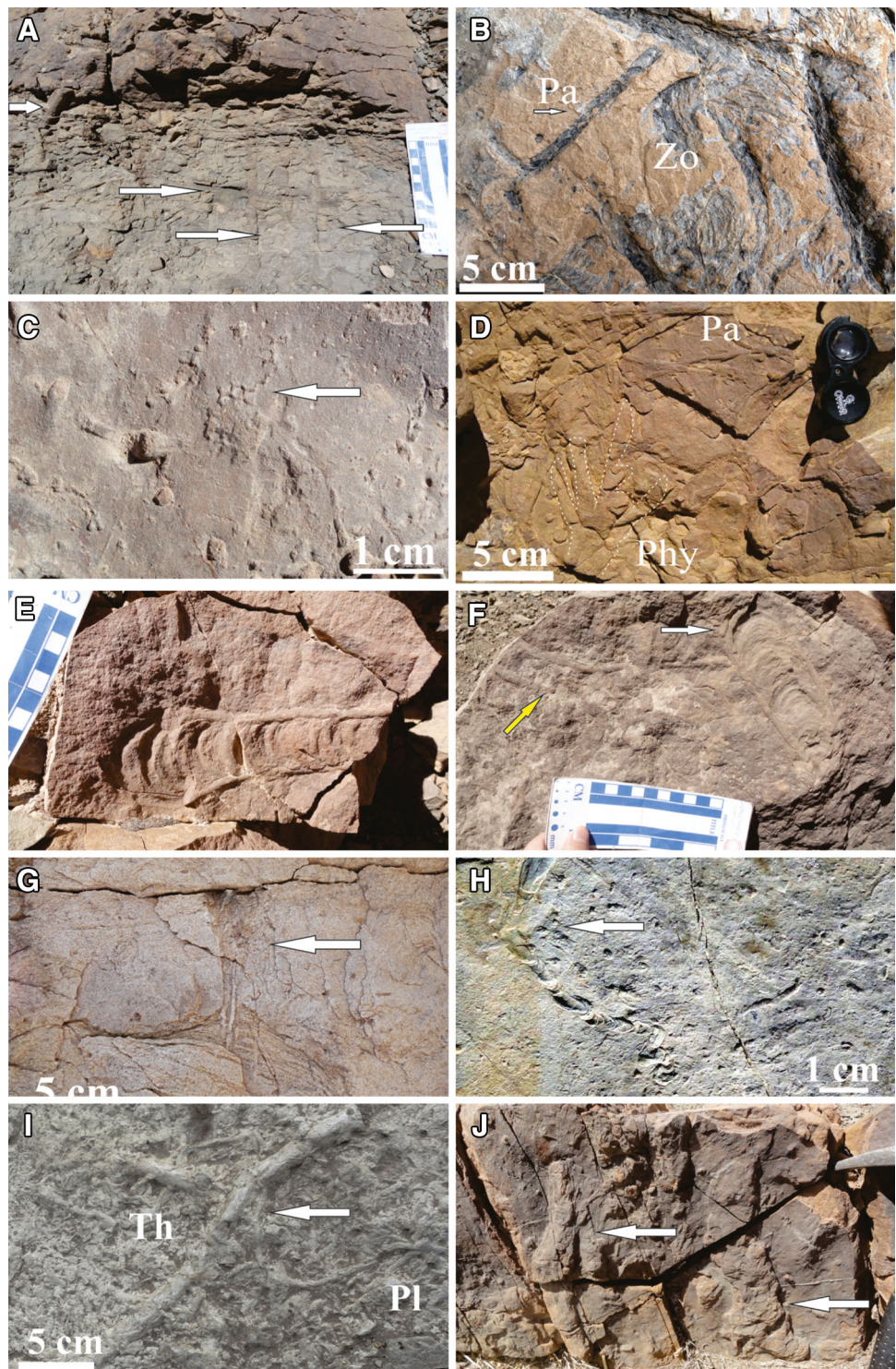
5.1.2 Facies B: distal delta front (distal mouth bar)

This facies is a heterolithic association of sharp-based, fine- to medium-grained sandstones and thinly inter-bedded siltstones, very fine-grained sandstones and massive mudstones (Fig. 5a, b) with synaeresis cracks, carbonaceous detritus and plant remains. Centimetre- to decimetre-thick sandstones with climbing ripple cross-lamination and Bouma Tab, Tabc and Tbc cycles are common within the distal delta-front deposits.

Deformed intervals typically lack bioturbation (BI0). In addition, composite graded bedsets are also typically not

burrowed. Bioturbation in this facies is sporadically distributed (BI 0–2), intensively burrowed centimetre-thick intervals with BI values up to 3–4 occur throughout. The suite is dominated by shallow-tier, simple, horizontal burrows (*Planolites* isp., *P. beverleyensis*, *Palaeophycus* isp.), cubichnia traces (*Bergaueria*) and mid-tier, endichnial, burrows (*Teichichnus*), surface detritus-feeders (*Rosselia*), and fugichnia. The subordinate suite shows sparse *Cylindrichnus* isp., *Gyrochorte* isp., *Asterosoma* isp., *Rhizocorallium jenense*, *Diplocraterion* isp., and *Skolithos* isp.. Biogenic disruptions of laminae or mantle and swirl structures (MS, Lobza and Schieber 1999) are common.

Fig. 4 **a** *Ophiomorpha* isp. **b** *Palaeophycus tubularis* (Pa) associated with *Zoophycos* isp. (Zo). **c** *Paleodictyon* isp. **d** *Palaeophycus striatus* with lined margins ornamented with longitudinal grooves, associated with *Phycodes* isp. (Phy). **e** *Rhizocorallium jenense*. **f** *Rhizocorallium irregulare* with variable dimension and irregular curvature of tubes (yellow arrow) cross-cut by *R. jenense* (white arrow). **g** *Rosselia* isp; a funnel-shaped burrow a central tube. **h** *Taenidium cameronensis* with chevron-shaped sediment packages. **i** *Thalassinoides suevicus* showing Y-shaped bifurcations; swelling at the point of bifurcation with smooth surface, associated with *Planolites* isp. (Pl). **j** Bilobed traces with slightly oblique scratch marks on two parallel ridges



Interpretation: Facies B reflects deposition within distal mouth bar settings of a river-dominated delta (e.g., MacEachern and Bann 2008). The massive mudstone beds and graded beds may record prolonged fluvial influx, and are characteristic of rapid sedimentation by waxing and waning hyperpycnal flows (Bhattacharya and MacEachern

2009; Tonkin 2012). The presence of extensive evidence of the close association of soft-sediment deformed beds, composite graded bedsets, massive beds, MS structures, carbonaceous/organic detritus and synaeresis cracks, is interpreted to represent deposition in proximity to river discharge and recurrent salinity fluctuations due to

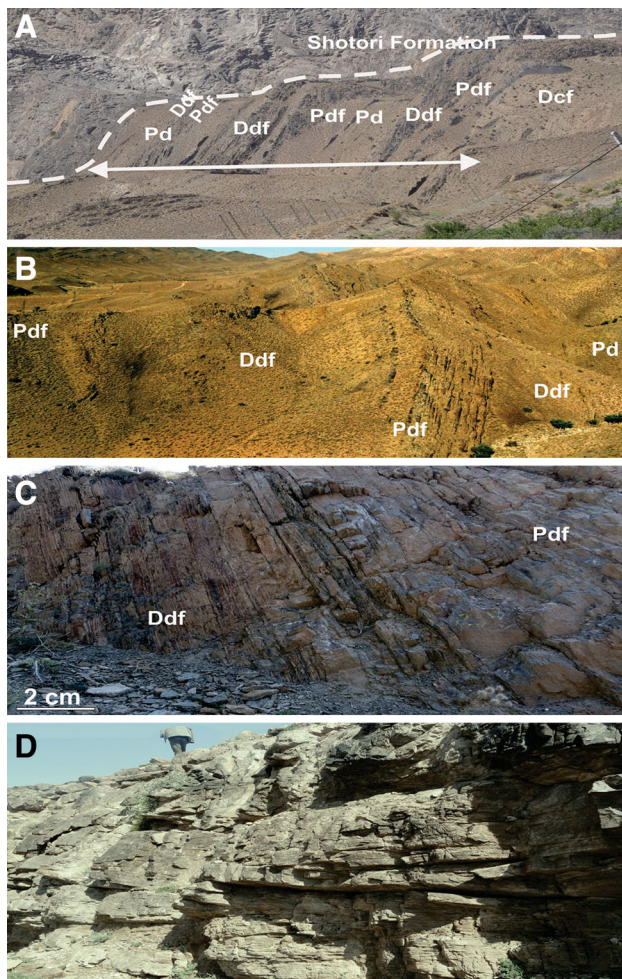


Fig. 5 **a** View of the lower member (Gelkan) of the Nayband Formation represented by prodelta, distal delta front, proximal delta front, and distributary channel of lower delta plain environments. **b** View of the complete progradational, coarsening-upward successions represented by the Gelkan member. *Pd* prodelta, *Ddf* distal delta front, *Pdf* proximal delta front. **c** Upward-thickening and coarsening association of heterolithic associations, distal delta front (*distal mouth bar*, *Ddf*), to sharp-based sandstones and siltstones, massive mudstone, proximal mouth bar facies (*Pdf*). **d** Lenticular sandstone with erosional base, forming fining-upward and thinning-upward intervals of distributary channel fills with planar, massive and trough-cross-stratification

hyperpycnal river plumes in flood-dominated deltaic systems (MacEachern et al. 2005; Bann et al. 2008). The trace fossil suites in this facies are “stressed” expressions of the *Cruziana* ichnofacies, which indicate depositional physico-chemical stresses for infaunal organisms (Gingras et al. 1998, 2011; MacEachern et al. 2005; Buatois et al. 2008, 2012; Bayet-Goll and Neto De Carvalho 2015).

5.1.3 Facies C: proximal delta front (proximal mouth bar)

This facies is an upward-thickening association of medium-grained, well sorted, flat bedded, tabular, amalgamated

sandstone beds with massive sandstone, planar cross-bedding, climbing ripple lamination, and rarely trough cross-bedding and hummocky cross-stratification (HCS). Wave ripples with carbonaceous/organic detritus, synaeresis cracks and soft-sediment deformation structures occur on the upper surface of the beds (Fig. 5a, c).

Bedsets within Facies C may be almost devoid of ichnofossils throughout significant thicknesses. The sandstones of Facies C comprise only sparse and sporadically distributed ichnofossils (BI0–1) of small size that are mainly horizontal, morphologically simple, facies-crossing structures (simple grazing, locomotion, resting traces). Sporadic intensively burrowed centimetre-thick intervals with BI values up to 3–4 occur throughout the mostly un-burrowed background. The shallowest tier consists of *Planolites* isp., *P. beverleyensis*, *Bergaueria* isp., *B. hemispherica*, *Gyrochorte* isp., bilobed traces, tracks, and *Macaronichnus* isp. Mid-tier structures (*Rhizocorallium jenense*, *Cylindrichnus* isp., *Rosselia* isp., and *Asterosoma* isp., *Asterosoma* cf. *radiciforme*, *Thalassinoides horizontalis*, *T. paradoxicus* and *Gyrolithes* isp.) show a patchy distribution. The subordinate suite comprises mid to deep-tier, domichnia structures (*Skolithos* isp., *Diplocraterion* isp., *Arenicolites* isp.). Escape traces (fugichnia) and MS structures occur in sandstones.

Interpretation: Based on sedimentological features and stratigraphic relations with the other facies, Facies C is interpreted to represent high sedimentation rates and sediment supply, caused by river discharge in mouth bars. The occurrence of wave-ripples and HCS beds suggests that storm waves sporadically reworked the delta front. However, the reduced wave influence and general lack of extensive storm reworking reflect rapid depositional rates which permit the preservation of massive (structureless) sandstone and gradational planar and climbing ripple laminations. Together with common convolute bedding intervals they are indicative of a high-deposition rate and subsequent loading and dewatering. The presence of extensive carbonaceous detritus reflect periodic fluvial influx consistent with close proximity to downdrift of distributary mouths (e.g., MacEachern et al. 2005; Bhattacharya et al. 2011). The reduced heterolithic association and mudstone content and the inferred high depositional rates, together with the ichnologic characteristics, indicate that Facies C was deposited in a more proximal position than Facies B. The trace fossil suite in this facies is attributable to a stressed/depauperate mixed *Skolithos-Cruziana* ichnofacies (e.g., Gingras et al. 1998; MacEachern et al. 2005, 2007b). Sporadic intensively burrowed centimetre-thick intervals may record short-lived returns to ambient conditions, probably related to pauses in fluvial influx.

5.1.4 Facies D: distributary channel fills

Facies D consists of thinning-upward, lenticular, medium- to coarse-grained sandstone beds with erosional base and, parallel lamination or unidirectional trough/planar-cross-stratification (Fig. 5d). They erosionally overlie mouth bars or delta-front deposits. The basal erosional surfaces are lined by clay-clast conglomerates or wood and plant fragments. Plant detritus, synaeresis cracks, and soft-sediment deformation structures occur locally.

Bioturbation is absent or sparse in the channel deposits and tends to be restricted to the uppermost part of the deposit, where it locally achieves moderate levels of intensity (BI0–1). Facies D contains shallow-tiers suites, represented by low diversity and high densities of opportunistic, simple feeding strategies of facies-crossing forms (*Planolites* isp., *Palaeophycus* isp., *Bergaueria hemispherica*). A subordinate suite occurs at mid-tiers and includes *Ophiomorpha* isp., *Thalassinoides paradoxicus* and *Arenicolites* isp.

Interpretation: The sand bodies with unimodal trough and planar cross-stratification overlying concave-upward erosional surfaces, and with wood and plant fragments suggest deposition in distributary channels of the lower delta plain. This facies sits above proximal delta-front successions, and was presumably deposited in terminal distributary channels (e.g. Buatois et al. 2008). The terminal position of distributary channels is documented by the sandstones resting with a distinct erosional base on the proximal mouth bar (Facies C). The trace fossil suite is attributed to the *Skolithos* ichnofacies (e.g., Gingras et al. 1998; MacEachern and Gingras 2007), possibly controlled by low salinity, high energy conditions, and/or episodic sedimentation.

5.2 Facies association B: offshore and shoreface deposits

5.2.1 Facies E: open shelf

This facies consists of mudstone and shale, locally interbedded with very thin to thin (1–3 cm), siltstone and fine-grained ripple-laminated sandstones with an erosional base (Fig. 6a, b). Interbeds of sharp-based, normal-graded to weakly rippled siltstones to fine-grained sandstones and mudstones occur throughout this facies. Skeletal remains include bivalves, brachiopods and sponge spicules.

The shale and muddy siltstone beds are characterized by highly variable bioturbation intensities, ranging from thick, very weakly bioturbated horizons (BI: 0–1) to alternating cm-scale bioturbated and non-bioturbated horizons (BI: 0–3). Bioturbated horizons in Facies E exhibit shallow to deep-tiers suites, represented by moderate diversity, low

bioturbation intensity (BI: 1–2), a high density of endichnial fodinichnia, endobenthic pascichnia traces, and other sparse feeding traces. Deep-tiers include endichnial fodinichnia (*Chondrites* and *Zoophycos*), the mid-tier fodinichnia (gastropods) traces (?*Scolicia*), and the shallow-tier fodinichnia and pascichnia (*Phycosiphon* isp., *Helminthopsis* isp., and *Gordia* cf. *marina*), and incomplete convex hexagonal meshes of *Paleodictyon* isp.

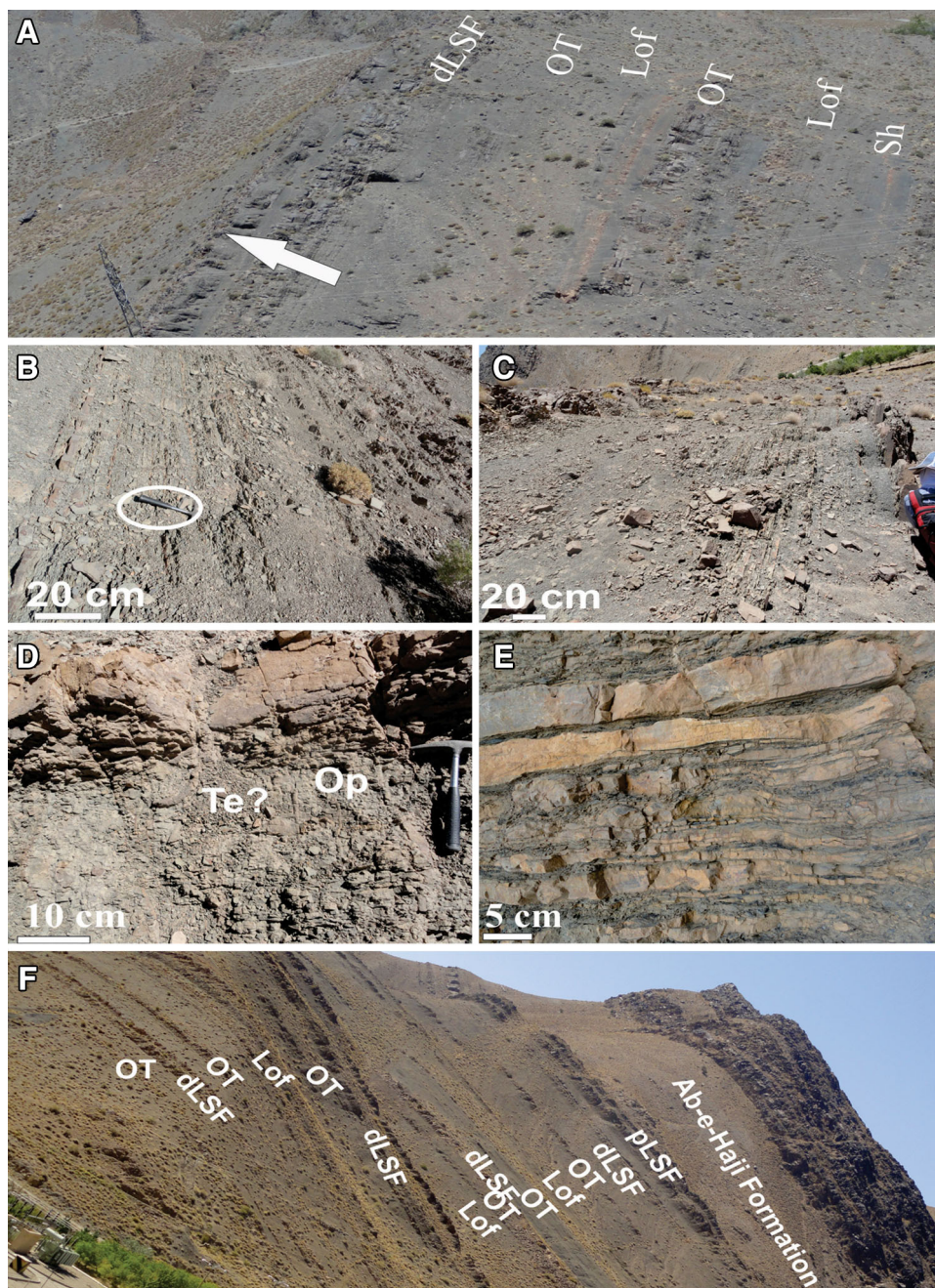
Interpretation: Based on sedimentological features and stratigraphic relations with the other facies, fine grain size, open-marine trace fossils, and common thin turbidite-like beds (flat- to ripple-laminated beds), Facies E is interpreted as turbidites on the shelf. The thin turbidite-like beds with sharp boundaries to the top may represent event flows, probably towards the offshore-shelf, followed by suspension fallout after high energy events (Mutti et al. 2003; Pattison 2005; Pattison et al. 2007; Bayet-Goll et al. 2015a). Due to its mud-dominated nature and prominent nektonic fauna, Facies E is related to suspension fallout in a shelf marine setting. In this setting, the sandier intervals probably were emplaced by shoreface-derived low-density flows following storms (Myrow et al. 2002) and/or dense fluvial bed loads forming turbid underflows on the sea floor (Mutti et al. 1996, 2003). The trace fossil suite in Facies E is assigned to the *Zoophycos* ichnofacies, characteristic of quiet marine shelf environments with low sedimentation rates, below storm wave-base (MacEachern et al. 2007a; Bayet-Goll et al. 2014a).

5.2.2 Facies F: lower offshore

Facies F comprises moderately to thoroughly bioturbated siltstone/mudstones and fine-grained sandstone locally with sparsely burrowed to non-burrowed fissile mudstone and muddy siltstones layers (Fig. 6a, c). Locally, cm-thick planar lamina sets are preserved, but the association is profusely bioturbated with much of the original depositional structure destroyed. The sandstone beds are characterized by parallel lamination, micro-HCS, combined-flow ripples, and symmetrical rippled upper surfaces. Body fossils are dominated by brachiopods, bivalves, and gastropods.

Bioturbation in Facies F is highly variable, ranging from homogeneous mudstone (BI 4–6) to sparsely to non-burrowed fissile mudstone (BI: 0–2). Bioturbation decreases in intensity in the thin sandstone beds (BI: 0–2). The ethological groupings represented in the suite are dominated by shallow-tier fodinichnia and pascichnia (*Planolites* isp., *P. beverleyensis*, *Helminthopsis* isp., *H. abeli*, *H. hieroglyphica*), mid-tier (*Scolicia* isp.) and deep-tier fodinichnia (*Zoophycos* isp., *Chondrites* isp., *C. intricatus*), associated with fewer domichnia/fodinichnia and repichnia (*Teichichnus* isp., *Rhizocorallium irregulare*, *Protovirgularia* isp., *Gyrochorte* isp.).

Fig. 6 **a** View of the Howz-e-Sheikh member of the Nayband Formation representing distal lower shoreface (dLSF), offshore transition (ot), lower offshore (Lof) and shelf (sh) environments. **b** Heterolithic association of sharp-based, sandstones/siltstones and mudstones, shelf facies. **c** Heterolithic association of parallel-laminated, moderately to thoroughly bioturbated siltstone/mudstones and fine-grained sandstone, lower offshore facies. **d** Heterolithic association of moderately to thoroughly bioturbated and massive sandstones/siltstone and mudstone; offshore transition facies with *Teichichnus* isp. (Te) and *Ophiomorpha* isp. (Op). **e** Sandstone beds characterized by micro-HCS, HCS and combined-flow ripple cross-lamination, offshore transition facies, HCS tends to be dominant in the thickest sandstone beds, whereas micro-HCS dominated in the thinner beds. **f** View of the upper member (Howz-e-Sheikh) of the Nayband Formation represented by proximal lower shoreface (pLSF), distal lower shoreface (dLSF), offshore transition (ot), lower offshore (Lof) and shelf (sh) environments



Interpretation: The strata of Facies F alternate between homogeneous mudstones of fair-weather origin and laminated sandstones representing distal tempestites within a lower offshore environment (Bayet-Goll et al. 2014b, 2017). Basal erosional surfaces in the sandier intervals formed under high-energy storm waves scour, whereas the mudstone formed under waning storm-energy conditions as suspended fines settled from suspension. These characteristics suggest that quiet continuous background sedimentation was overprinted by episodic storm deposition. The presence of marine invertebrate fossils also points to a quiet-water, open marine setting. The trace

fossil assemblage is a distal expression of the *Cruziana* ichnofacies (MacEachern et al. 2007a) or, in some cases, can be considered as intergradational with the *Zoophycos* ichnofacies.

5.2.3 Facies G: offshore transition

This facies is dominated by moderately to thoroughly bioturbated, interbedded mudstones, silty mudstones, and thin to thick (0.5–20 cm), laterally extensive, basally scoured, fine- to very fine-grained sandstones and sandy siltstones (Fig. 6d). Locally, the sandstone beds are

characterized by micro-HCS, HCS, wave-ripple lamination and/or symmetrical ripples at the top (Fig. 6e). HCS tends to be dominant in the thickest sandstone beds, whereas micro-HCS is dominant in the thinner beds. Amalgamation of hummocky beds is uncommon. Sandstone beds commonly exhibit gutter casts at their base. Beds are stacked, forming coarsening-upward and thickening-upward packages. Body fossils are locally abundant, dominated by brachiopods, bivalves, corals, and bryozoans.

The degree of biogenic reworking is variable due to changes in substrate characteristics (sand-silt ratio) and depositional history (deposition vs. erosion). Bioturbation in Facies G commonly ranges from BI 1 to BI 6. The degree of bioturbation in the background mudstone is typically high, with intervals totally or almost totally homogenized (BI: 5–6). Where bioturbation in the silty mudstones and siltstone beds is not complete (BI: 3–4), the ethological groupings are dominated by a mixture of pas-cichnia, repichnia, cubichnia (shallow-tier), complex fodinichnia, domichnia-fodinichnia (mid-tier), and endichnial deposit-feeders (deep-tier). The ichnoassemblage of muddy intervals consists of *Rhizocorallium* isp., *R. irregulare*, *Protovirgularia* isp., *P.* cf. *rugosa*, *Helminthopsis* isp., *Planolites* isp., and *Palaeophycus* isp. The subordinate suite comprises *P. tubularis*, *P. heberti*, *Cylindrichnus* isp., *Bergaueria* isp., *B.* cf. *perata*, *Thalassinoides* isp., *R. jenense*, *Gyrochorte comosa*, *Zoophycos* isp., *Chondrites* isp., *Taenidium* isp., *T. cameronensis*, and *?Rosselia* isp. In contrast, the well-laminated sandstone beds are less intensely bioturbated (BI: 0–2) and are dominated by mid/deep-tier, domichnia structures (*Ophiomorpha* isp., *R. jenense*, *Skolithos* isp.) and domichnia-fodinichnia (*Palaeophycus* isp., *Thalassinoides horizontalis*, *T. suevicus*). The subordinate suite in sandy intervals comprises *Bergaueria* isp., *O. nodosa*, *O. irregulaire*, *Arenicolites* isp., *Planolites annulatus*, and *Diplocraterion* isp.

Interpretation: Based on sedimentological features and stratigraphic relations with the other facies, Facies G is interpreted to represent deposition in a transition-zone environment, below the fair-weather wave-base but above the mean storm wave-base. HCS and wave-ripple lamination are typical of storm deposits formed under the influence of combined-flow, and point to an environment affected primarily by waves rather than currents (Cheel and Leckie 1993; Bayet-Goll et al. 2015a, b). Interbedding of sandstone and mudstone would have been produced by alternating storm and fair-weather conditions (e.g., Buatois et al. 2012). The trace fossil assemblage is attributed to the *Cruziana* ichnofacies, alternating with opportunistic suites of the *Skolithos* ichnofacies recording colonization of event beds (Pemberton and MacEachern 1997).

5.2.4 Facies H: distal lower shoreface

Facies H consists of interlaminated and interbedded highly bioturbated mudstones, silty mudstones, siltstones and sandstones (Fig. 6a, f). Sandstone beds are generally massive and homogeneous or sharp-based, fine-grained with internal planar, low-angle and hummocky cross-stratification. Intercalated mudstones and silty mudstones are commonly planar-laminated, often with thin sandstone laminae and lenticels of wave-ripples. In contrast to Facies G, this facies has thicker sandstone beds and less abundant and thinner mudstones beds. Amalgamated sandstones are less common and may comprise up to 30–40 cm thick bedsets. Basal contacts are sharp and show locally evidence of scouring. In general, sedimentary structures in Facies H show an upward loss of oscillation ripple laminae and muddy interbeds, and an increase in the thickness and abundance of planar lamination, and hummocky cross-stratified and massive sandstones. Towards the top of the succession the sandstone beds thicken and become more common. This amalgamation marks the transition to the overlying Facies I. Body fossils are locally abundant.

Facies H is characterized by highly variable bioturbation intensities, ranging from BI 0 to BI 4. Intensive bioturbation (BI 4–5) occur locally. Bioturbation and trace fossil distribution is more or less persistent within the mudstone beds, but sporadically distributed in the laminated sandstone layers. Facies H is characterized by complex shallow to deep-tiers. Facies H is dominated by a mixture of shallow to mid-tier fodinichnia/domichnia with spreiten (*Rhizocorallium jenense*, *R. irregulare*) mid to deep-tier domichnia to fodinichnia structures (*Diplocraterion* isp., *Arenicolites* isp., *Ophiomorpha* isp., *O. irregulaire*, *Skolithos* isp.) and shallow-tier horizontal, simple fodinichnia (*Planolites* isp., *Palaeophycus* isp., *P. heberti*). The subordinate suite comprises shallow-tier *Lockeia* isp., *Protovirgularia* isp., *Taenidium* isp., *Cochlichnus* isp., *P. striatus*, *P. annulatus*, *Bergaueria* isp., and *Gyrochorte* isp., and mid-tier *Thalassinoides paradoxicus*, *T. suevicus*, and *Phycodes* isp.

Interpretation: Rhythmically bedded fine- to medium-grained sandstones with mm-to-cm-thick mudstone–siltstone interlaminations demonstrate variations in water energy and sedimentation rates. HCS and low-angle planar cross-stratification can be produced by waning oscillatory flows created by storm events (e.g., Pemberton and MacEachern 1997; Bayet-Goll et al. 2017). Furthermore, the fine-grained, bioturbated lithology of Facies H indicates a rather quiet environment during fair-weather periods. Therefore, it is interpreted as being deposited above storm wave-base, but below fair-weather wave-base in a distal lower shoreface setting, sandstone tempestites being capped by layers of mudstone during fair-weather episodes

(Hampson and Storms 2003; Bayet-Goll et al. 2015b). The trace fossil suite is attributed to a proximal expression of the *Cruziana* ichnofacies intergradational with the distal *Skolithos* ichnofacies (e.g., MacEachern et al. 2007a).

5.2.5 Facies I: proximal lower shoreface

This facies is composed mainly of tabular sandstone beds, typically 0.2–0.6 m thick (Fig. 6f). These beds are well sorted and are defined by thick planar to low-angle planar cross-stratification and HCS, interbedded with bioturbated muddy sandstone. Facies I is made of amalgamated sandstone layers, which are in gradational contact with underlying units of Facies H. In this respect, bedsets within this facies reflect upward-thickening deposits of the distal lower shoreface facies. These beds can be erosionally amalgamated and locally interbedded with bioturbated muddy sandstone.

Facies I is characterized by highly variable bioturbation intensities, ranging from BI 0 to BI 3. Bioturbation and trace fossil distribution is more or less persistent within the muddy sandstone beds but sporadically distributed in the laminated sandstone layers. Tiering is characterized by abundant mid-tier inclined, protrusive, U-shaped burrows of domichnia (*Rhizocorallium* isp., *R. jenense*) and mid- to deep-tier domichnia structures and fodinichnia/domichnia (*Ophiomorpha* isp., *Skolithos* isp., *Arenicolites* isp., *Thalassinoides suevicus* and *Diplocraterion* isp.). The subordinate suite comprises shallow-tier *Planolites* isp., *Bergaueria* isp., and *Palaeophycus* isp. Intensive bioturbation (BI 4–5) as a pipe-rock ichnofabric of *Skolithos* isp., *Monocraterion* isp., and *M. cf. tentaculatum* also occur locally.

Interpretation: Vertical amalgamation of beds, the scarcity or absence of mudstone layers between storm sandstone layers in combination with upward-coarsening grain size, and the sequence of sedimentary structures reflect high-energy conditions and progressive sorting associated with reworking by waves and currents in the lower shoreface above the fair-weather wave (Hampson and Storms 2003; Bayet-Goll et al. 2015b). The bioturbated sandstone beds contain a relatively diverse trace fossil suite that is a distal expression of the *Skolithos* ichnofacies, consistent with sedimentation within the more proximal portion of the lower shoreface (e.g., Bann and Fielding 2004).

6 Discussion

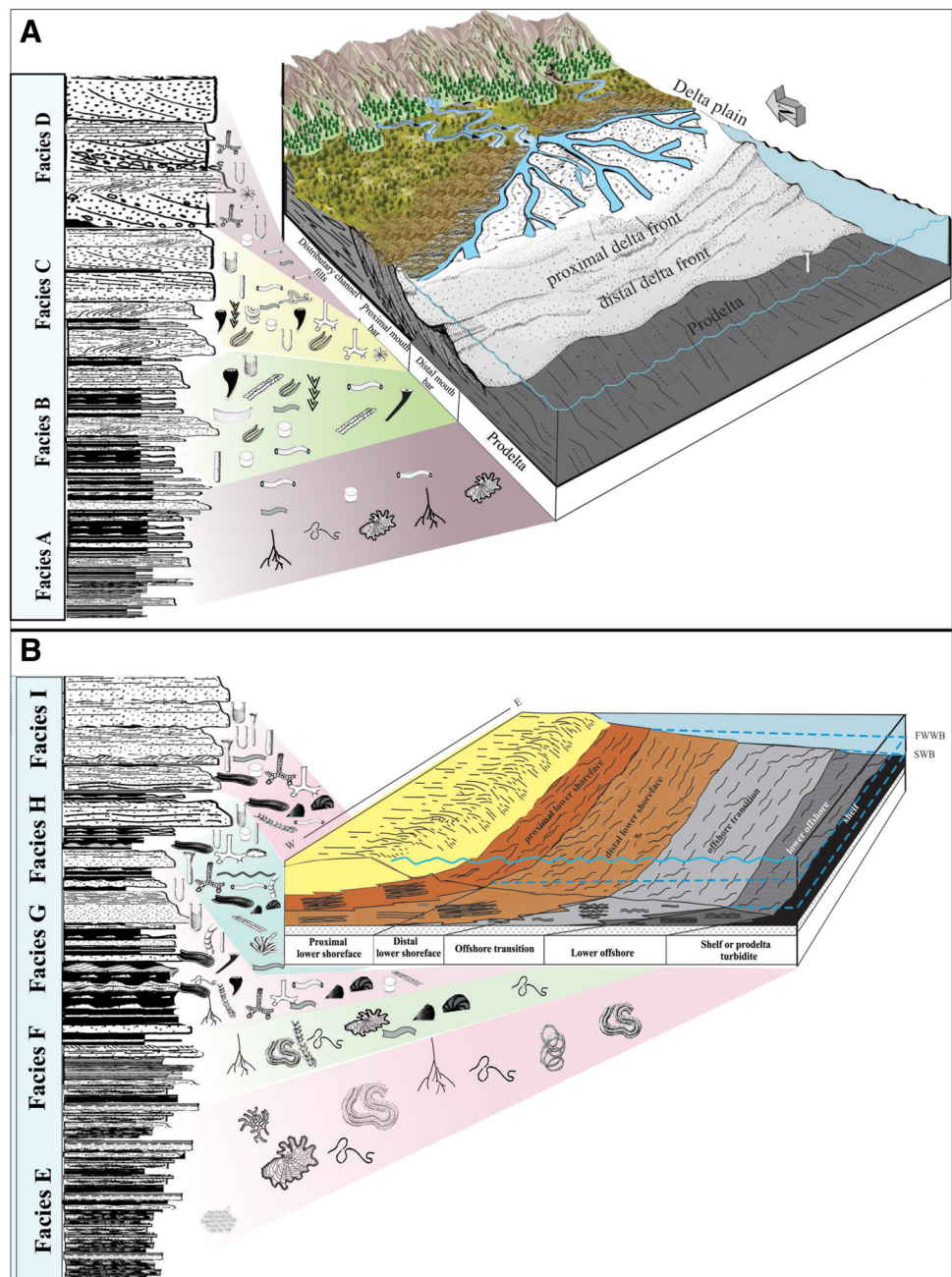
6.1 Depositional systems

The classification of facies association A (FA) as a river-dominated delta succession (Bhattacharya and Walker 1992) was originally based principally on sedimentological

evidence (Fig. 7a). Based on the above facies interpretations, the coarsening-upward succession that characterizes facies A, B and C is thought to represent a progradational unit in which river-influenced delta deposits are overlain by distributary channel fills deposits (facies D). The coarsening-upward sand-bodies are interpreted as prograding mouth bars of a river-dominated delta. Sand-body thicknesses range from 5 to 15 m and, in plan-view, display digitate or lobate morphologies. The delta model (Fig. 7a) is based on facies interpretations, and predicts thick accumulations of sand deposited in upd rift areas and greater amounts of fine-grained, heterolithic deposits lying in downdrift and prodelta areas. Such geometries suggest minimal reworking by basinal processes (e.g., waves; cf. Bhattacharya and Walker 1992) within the delta complexes of facies association A, and support the facies-driven interpretation of FA successions as more river-dominated. In particular, the coarsening-upward arrangement of the sedimentary facies and the lenticular cross-section of sedimentary bodies, which suggest a lobate outline, are coherent with a deltaic depositional setting, as demonstrated by numerous studies (e.g., Gingras et al. 1998; Pattison et al. 2007; Bhattacharya et al. 2011; Hurd et al. 2014). A wave-dominated deltaic environment for FA can be ruled out based on the absence of storm/wave indicators, the lack of sandy tempestites, a marked reduction in the diversity and abundance of infauna. Additionally, the abundant convolute-bedded intervals in FA reflect repeated episodes of slope failure in proximal delta-front and distal delta-front settings, due to the greater proportions of increased sediment influx, consistent with close proximity to distributary discharge (e.g., Gingras et al. 1998; Hurd et al. 2014). Synaeresis cracks developed due to salinity variations related to variable fluvial discharge (e.g., Gingras et al. 1998), and the presence of organic detritus and plant fragments due to periodic fluvial influx reflects close proximity to downdrift of distributary mouths (e.g., MacEachern et al. 2005; Tonkin 2012).

In the Nayband delta model (Fig. 7a), it appears that the currents were catastrophic events superimposed on the normal sedimentation patterns. The delta model predicts significant, along-strike variations in facies distributions between upd rift and downdrift portions of a river-influenced delta. In the Nayband delta, the upd rift deposits were mainly dominated by unidirectional, massive or cross-stratified sandstones, which indicate that friction-dominated deposition of sand grains were introduced into the basin during these periods with homopycnal or hypopycnal mixing style. According to Tonkin (2012), during periods of low discharge in the distributaries with homopycnal or hypopycnal mixing style, increase local mixing at the river mouth caused appreciable sedimentation around this point, especially sand deposition from bedload transport in the

Fig. 7 Schematic sedimentological models of the siliciclastic Nayband Formation in the study area, showing prodelta-delta front facies (a) and shelf-offshore-shoreface facies (b)



mouth bar area. In contrast, in the Nayband delta, the downdrift heterolithic deposits were dominated by density currents alternating with mudstone deposition. The land- to seaward changes in the facies between updriфт and downdrift portions of the Nayband delta suggest that hyperpycnal flows prevailed during major floods. Hyperpycnal flows passed below the basin waters as density currents causing sediment to be deposited on the lower delta front or on the prodelta (MacEachern et al. 2005, 2007b; Tonkin 2012). In this view, the thin turbidite-like beds in the downdrift portions of the Nayband delta were deposited under waxing and waning flow conditions, and are

indicative of deposition from high-density underflows (Mutti et al. 2003; Pattison et al. 2007; Bhattacharya and MacEachern 2009; Hurd et al. 2014). Based on the above facies interpretations, it seems that a favorable combination of high-discharge periods, low water salinity and shallow water depths in the mouth bar area resulted in the generation of flood-generated hyperpycnal flows. Generation of high-density underflows related to flood generated hyperpycnal flows was probably enhanced by the relatively fine grain-sizes supplied to the Nayband delta, which were fine enough to be carried in turbulent suspension in the river towards the prodelta area. The abundance of carbonized

detritus and organic plant remains in the downdrift portions of the Nayband delta supports the presence of flood-generated hyperpycnal flows.

In contrast, the common wave-/storm-induced structures, such as HCS and wave-ripple cross-lamination in facies association B (FB, Fig. 7b), are interpreted as having formed in response to strong, waning oscillatory currents, implying deposition of hummocky cross-stratified sandstone beds during storms and mudstone interbeds during intervening fair-weather periods (e.g., Cheel and Leckie 1993). The wide variety of grading patterns and internal sedimentary structures in the event beds of the FB indicate that many beds were deposited in relatively shallow water under the influence of combined flows with current and wave components. As storm-generated flows moved into deeper water they started to decelerate, resulting in less significant erosion of the sea floor and increased deposition, to form more continuous and regular beds (Bayet-Goll et al. 2015b). Sedimentological and ichnological data indicate distinct progradational stacking patterns in the FB. The upward change from offshore shelf deposits with interbedded bioturbated mudstones and sandstones to thickly amalgamated sandstones beds of the lower shoreface, coincident with increasing grain size, indicates an increase in depositional energy resulting in shoreface to offshore sand buildup.

6.2 Palaeoecological and palaeoenvironmental implications

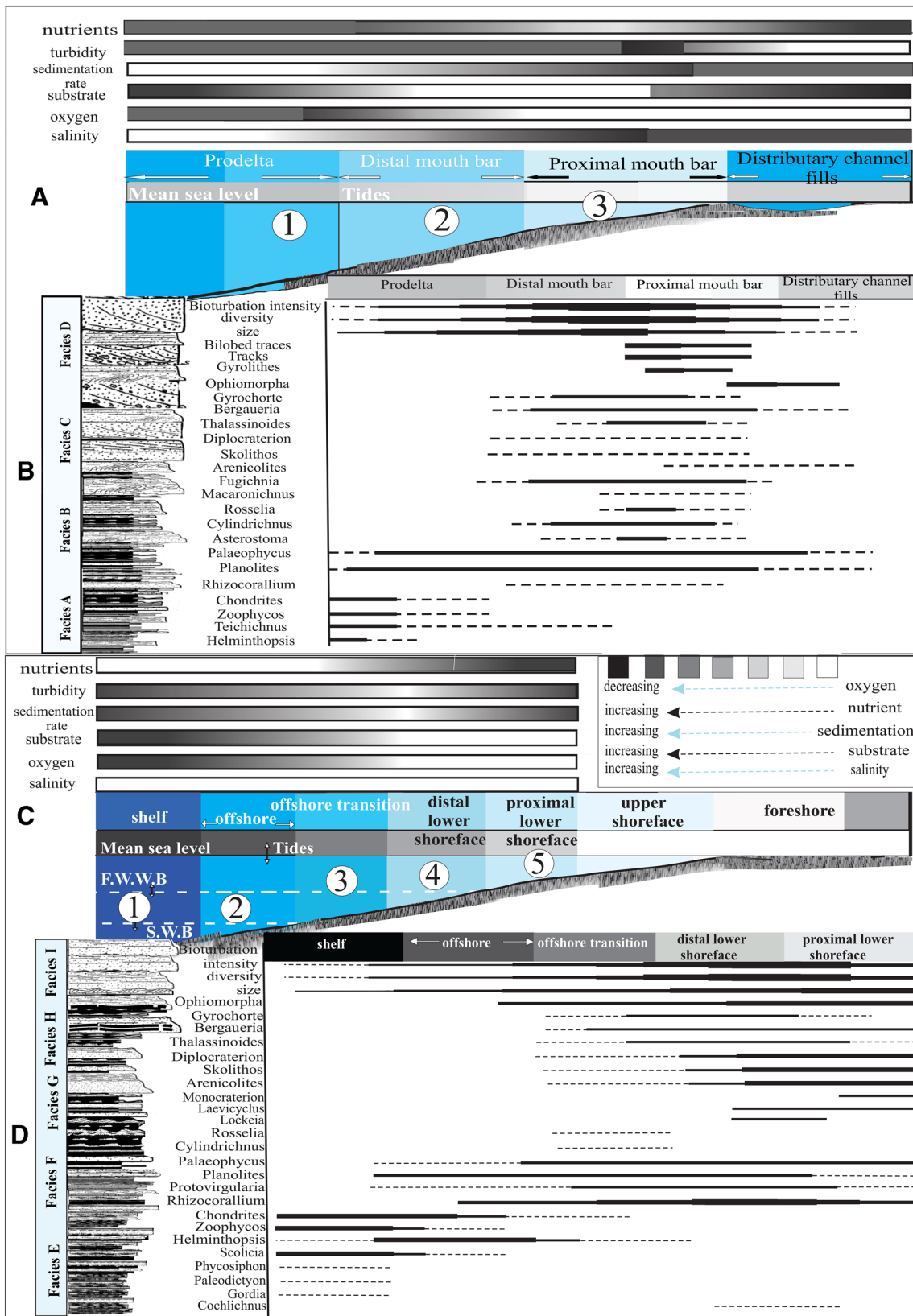
Identification and interpretation of departures from the archetypal ichnofacies are used to further refine palaeoenvironmental interpretations. In the present study, ichnological attributes include diversity (trophic types and ethologic groups), degree of bioturbation, trace fossil forms and complexity, size variations among ichnotaxa, tiering, and colonization style. These have been predominantly used to refine palaeoecological and palaeoenvironmental interpretations (Fig. 8).

6.2.1 Ichnodiversity (trophic types and ethologic groups)

Ichnodiversity in this study is expressed by the total number of ichnospecies and ichnogenera in both facies associations, fluvial-dominated delta (FA), and open marine (FB), and by ethological inferences (the behavioural classification) (Frey and Pemberton 1985; Bromley 1996) in order to understand the characteristic behaviour (ethology) of trace-makers in different environments. The low ichnodiversity but high density of individual ichnotaxa, dominated by horizontal, simple feeding strategies (such as *Planolites*, *Palaeophycus*,

Fig. 8 a Graphical representation of the characteristic sedimentological features and ichnofossils of Facies association A (river-dominated delta succession) with general position (i.e., proximal–medial–distal) of each ichnofacies related to different sub-environments. **b** Along-strike variations in ichnological characteristics reflecting spatial changes in prevailing physico-chemical conditions and range of occurrence and maximum cited abundance of each ichnotaxon. (1) Stressed distal expression of the *Cruziana* ichnofacies, prodelta, (2) “stressed” expression of the *Cruziana* Ichnofacies, distal delta front, (3) stressed/depauperate mixed *Skolithos*–*Cruziana* ichnofacies, proximal delta front. (4) Stressed *Skolithos* ichnofacies, distributary channel fills. **c** Graphical representation of the characteristic sedimentological features and ichnofossils of Facies association B (wave-dominated open marine succession). **d** Along-strike variations in ichnological characteristics (**b**). (1) *Zoophycos* ichnofacies, shelf, (2) distal expression of the *Cruziana* ichnofacies intergradational with the *Zoophycos* ichnofacies, lower offshore, (3) mixed *Cruziana*–*Skolithos* ichnofacies, offshore-transition, (4) proximal expression of the *Cruziana* ichnofacies, distal lower shoreface, (5) distal expression of the *Skolithos* ichnofacies, proximal lower shoreface

Bergaueria, *Rosselia*, and *Cylindrichnus*) and the paucity of *Skolithos* ichnofacies related structures, may represent a dominantly opportunistic colonization strategy of newly deposited sediment (r-selected ichnotaxa). The common burrow systems of worm-like endobenthic deposit feeding organisms or of detritus-feeders that systematically mined nutrient-rich layers is related to “stressed” ichnological suites. In general, the opportunistic colonization phase of the superficial organic rich layers (muddy sediment due to hyperpycnal flows), is commonly characterized by suites with a low ichnodiversity but high density of individual ichnotaxa, dominated by forms with simple morphologies. The reduction of diversity of ichnotaxa implies deterioration of the benthic ecosystem in the deltaic successions. However, the thin heterolithic intervals with high diversity in prodelta and delta-front environments (e.g. *R. jenense*, *Gyrochorte*, *Protovirgularia*, bilobed traces, tracks and *Gyrolithes*) are unusual in “stressed” ichnological suites, and probably reflect periods of low river discharge leading to mixing of the homopycnal and/or hypopycnal style (e.g., MacEachern and Gingras 2007; Buatois et al. 2008). In contrast, the trace-fossil suites in open marine deposits of the Nayband Formation show a high ichnological diversity including a complex mixture of structures produced by suspension-feeding, deposit-feeding and grazing/foraging behaviours. The common occurrence of diverse trace fossil suites attributable to grazing, foraging and deposit feeding behaviours on more cohesive fine-grained substrates (such as *Rhizocorallium*, *Protovirgularia*, *Helminthopsis*, *Planolites*, *Gyrochorte*, *Zoophycos*, *Chondrites*, *Taenidium* isp.) point to stress-free conditions in open marine settings with a wide colonization window (Gingras et al. 1998; Hansen and MacEachern 2007; Bhattacharya et al. 2011; Bayet-Goll et al. 2015b, 2017).



6.2.2 Extent of bioturbation

The bioturbation index in this study is used as a semi-quantitative indicator of the abundance of trace fossils and burrowing pattern (Taylor and Goldring 1993; Gani et al. 2008). The trace fossil suite in the deltaic successions is reduced with respect to uniformity of burrowing and degree of bioturbation compared with their non-deltaic shoreface counterparts and shows the most “non-uniform” trends (see Gani et al. 2008) and highly variable values of BI (ranging from BI0 to BI4 and typically BI0–2 h local spikes in intensity: (3–4). The largely non-burrowed nature of the river-dominated deltaic successions with sporadic distributions of burrowing and non-uniform trends that contain horizontal, simple feeding burrows (see MacEachern et al. 2007b; MacEachern and Gingras 2007), is thought to result from high physico-chemical stress induced by frequent hyperpycnal flows. High rates of fluvial discharge, high water turbidity, seasonally high rates of deposition and phytodetrital pulses in river-dominated deltas may cause marked variations in the temperature, oxygenation and salinity of the sub-basin (e.g., Coates and MacEachern 1999). The combination of all these factors led to a decrease in the diversity and abundance of ichnotaxa, only sporadic burrowing (non-uniform) and lower intensities of bioturbation in the river-dominated deltaic successions of the Nayband Formation. The bioturbation spikes between the deltaic successions are indicative of intermittent periods of higher favourable conditions for infaunal and epifaunal organisms living between river-flood events, when the delta area was returned to normal marine conditions or during times of hypopycnal conditions (e.g., Gani et al. 2008; Bhattacharya et al. 2011). On the contrary, the higher bioturbation index (high abundance) and uniform bioturbation in the open marine deposits reflects slow or discontinuous sedimentation, lower environmental stress, and sufficient time for the tracemakers to disturb bottom sediments. In this view, the high bioturbation intensity possibly reflects decreased turbidity levels, increased food concentrations and oxygen levels, and a relatively stable substrate. Overall, uniform distributions of burrowing suggests that food resources were randomly distributed rather than concentrated in organic rich layers. It should be noted that basinward the bioturbation index and uniform bioturbation are reduced due to a marked decrease in oxygenation of the interstitial waters. For this reason, maintaining an open connection to the sediment–water interface was required for burrowing organisms such as *Zoophycos*, *Chondrites*, and *Teichichnus*.

6.2.3 Trace fossil morphology and complexity

The complexity is analyzed on the basis of the reconstructed morphology of the burrow system in both facies

associations. The gradational increases/decreases in the complexity of trace fossils were influenced by environmental parameters. The deltaic successions of the Nayband Formation are typically characterized by an abundance of certain very simple infaunal burrows and epifaunal trails of non-specialised behaviour, shallow tiering, and the absence of large burrows and complex trace systems. In contrast, trace fossil assemblages of the open marine deposits are characterized by an increased complexity of burrow systems and consequently of behavioural complexity of the producers predominantly crustaceans (*Thalassinoides*, *Ophiomorpha*, *Rhizocorallium*, and *Gyrolithes*), bivalves (*Lockeia*, *Protovirgularia*, *Gyrochorte*), gastropods (?*Scolicia*). It seems that increase in the competition for food and further improvement of the marine ecosystem due to diversification of faunas favoured diversity of behavioural adaptations and consequently the great diversity of behavioural complexity of trace fossils (Bayet-Goll et al. 2016c). However, in lower offshore-shelf environments, towards the basin center, the absence of complex trace fossils and lower abundance and depth of infaunal structures, mainly of deposit-feeders suggest a very soft to soupy substrate with a low oxygen content (MacEachern and Bann 2008; Gingras et al. 2011, b).

6.2.4 Size variations among ichnotaxa

The sizes of burrows were measured on bedding surfaces of both facies associations. Trace-fossil size has been taken as a proxy for the body size of the tracemakers (e.g., Savrda and Bottjer 1986). The environmental stress associated with brackish environments of the deltaic successions and habitats with a low nutrient supply and low oxygen concentrations in lower offshore shelf environments resulted in a decrease in body size within the endobenthic community, manifested by a smaller burrow diameter (e.g., Savrda 1992; MacEachern and Gingras 2007). A significant increase in burrow size, especially in trace fossils constructed predominantly by crustaceans and bivalves occurs in the shoreface ichnoassemblage. In contrast, in the basinward direction, decreasing oxygen availability waters cause a noticeable reduction in the size of the burrows, their abundances, and their diversity, as shown by the highly abundant small traces of endichnial deposit-feeding, deposit-feeding and grazing and scavenging organisms (*Chondrites*, *Phycosiphon*, *Helminthopsis*, *Planolites*, *Palaeophycus*, *Teichichnus* and *Gordia*).

6.2.5 Infaunal tiering and colonization style

Tiering profiles were used to describe and identify colonization styles (Bromley and Ekdale 1986). The deltaic successions of the Nayband Formation are characterized by

abundant primary sedimentary structures or massive bedding, thick non-burrowed strata and reduction in the diversity of trace fossils resulting in simple tiering patterns. The colonization style is characterized by abundant opportunistic organisms that were trophic generalists (see MacEachern and Gingras 2007; MacEachern et al. 2007b). The deltaic successions exhibit shallow to mid-tiers, reflecting simple colonization events and represented by simple grazing burrows and resting traces (shallow-tier), and burrows of surface detritus-feeders (mid-tier), and by traces of deposit-feeders (deep-tier). The stress produced by brackish conditions in parts of the deltaic successions resulted not only in the reduction of burrow diameter but also of tier depth. The lack of a deep-tier, produced by generally opportunistic, multi-layer colonizers, and the widespread shallow-tier, produced by single-layer colonizers suggest a stressed environment. Therefore, the preferential preservation of the shallow-tier near the sediment/water interface and the general lack of complex tiering structures might suggest rapid colonization of newly available substrates during phases of reduced water energy and/or sedimentation rate. It seems that high density-currents that produced increased stress probably significantly deterred burrowing and led to single colonization events. High levels of suspended sediment caused by river discharge might have inhibited the colonization by suspension feeding organisms, whose deep-galleries are common in sandy substrates as and remain stationary for long periods of time (Bromley 1996; Pemberton et al. 2001). Generally, rapid colonization of new substrate by opportunistic deposit feeders indicates that the sedimentation rate was relatively high, preventing burrowing organisms to keep up with the accumulation rate and to rework the sediment.

In contrast, the changes in trace fossil composition or behavioural complexity and in the tiering pattern in the offshore-shoreface complex represent the transition from epifaunal life habits with simple tiering structures to infaunal life habits with complex tiering patterns. The trace-fossil suites reflect multiple colonization events and complex tiering patterns (shallow to deep). Colonization is characterized by abundant traces of suspension-feeders and domichnia/fodinichnia (deep-tier), surface detritus-feeders, grazing/foraging traces (shallow/mid-tier), and fodinichnia and repichnia (shallow-tier). The common occurrence of more complex traces or sophisticated feeding strategies and the considerable increase in the abundance and depth of infaunal structures are indicative of the vertical partitioning of the ecospace and multiple colonization events. The latter reflect a stress-free, stable environment with homogeneous distribution of food, normal salinity, and oxygenated waters and hence, a wider colonization window. The development of complex tiering patterns and the increase in depth of burrowing could represent the extensive

utilization of the infaunal ecospace and vertical niche partitioning (e.g., Carmona et al. 2008). It should be noted that, although the occurrence of high abundance of surface grazing and deposit-feeding behaviours indicate inhabitation of tracemakers on cohesive fine-grained substrates typical of quiet-water, fully marine conditions well below fair-weather wave base. However, high-energy, storm-dominated settings probably may cause a low diversity of trace fossils, low degree of bioturbation and the dominance of deep-tier structures.

6.3 Comparisons with other Triassic ichnofaunas

Early Triassic ichnoassemblages typically exhibit low ichnodiversity, typically diminutive in size with abundance of certain very simple infaunal burrows and epifaunal trails, non-specialised behaviour, shallow-tiering, presence of monospecific suites, and the absence of large burrows and complex trace systems (e.g., Twitchett 1999; Fraiser and Bottjer 2009; Chen et al. 2011, 2012; Zhao et al. 2015). As demonstrated by this and numerous other studies (e.g. Twitchett 1999; Rodriguez-Tovar et al. 2007; Knaust 2007, 2013; Mörk and Bromley 2008; Rodriguez-Tovar and Perez-Valera 2008; Fraiser and Bottjer 2009; Jaglarz and Uchman 2010; Knaust and Costamagna 2012; Knaust et al. 2012; Chrzastek 2013), ichno-assemblages markedly increased in behavioural complexity, burrow diameter, diversity, bioturbation intensity and tier depth during Middle–Late Triassic times. Most authors presume that marine ecosystems suffered from a major diversity loss and did not recover from the end-Permian extinction event until the onset of the Middle Triassic (Twitchett 1999; Twitchett et al. 2004; Fraiser and Bottjer 2009). In this regard, the high diversity and bioturbation intensity of the Nayband trace fossil suites seem to represent the proliferation of epifaunal and infaunal habits, leading to a diversification of marine communities after the drastic reorganization of marine ecosystems the Early-Middle Triassic. This diversification of trace fossil suites recorded in the beds of this study, is in agreement with diversification events recorded by diverse benthic shelly macrofaunal communities (e.g. Fürsich and Wendt 1977; Kelley and Hansen 2001).

Expanded sections spanning Late Triassic shallow- and deep-water environments in Central Iran and comparisons with other Triassic ichnofaunas help to understand the environmental and biological causes and consequences of the palaeoenvironments and the drastic reorganization of marine ecosystems during the Late Triassic. The Late Triassic Nayband Formation in central Iran contains diverse reefs, and a rich fauna of algae, foraminifers, sponges, corals, hydrozoans, brachiopods, gastropods, bivalves, ammonoids and echinoderms (Nützel et al. 2003; Seyed-Emami 2003; Cirilli et al. 2005; Senowbari-Daryan

2005; Fürsich et al. 2005, 2009). According to Senowbari-Daryan (2005) coral-sponge or sponge-coral dominated reefs occur within the Bidestan and Howz-e-Khan members of the Nayband Formation. These reefs combined with a rich macrofauna inhabiting level support a normal condition of the ecosystem during the Late Triassic (e.g., Fürsich et al. 2005, 2007, 2009).

The diversification of marine faunas greatly increased the diversity of the primary producers in marine environments and thus, in turn, it caused the reorganization of other metazoan and enhance variable tracemaker behaviours. Consequently, increase in the competition for food and further improvement of the marine ecosystem due to diversification of faunas favoured diversity of behavioural adaptations and consequently the great diversity of ichnospecies. Based on the ichnotaxonomic composition illustrated in this and others studies (e.g. Knaust 2007; Rodriguez-Tovar et al. 2007; Jaglarz and Uchman 2010; Knaust and Costamagna 2012; Knaust et al. 2012; Chrzastek 2013) the abundance of trace fossils constructed by crustaceans, bivalves, gastropods underwent a diametrical rise during the Middle/Late Triassic. Due to the nature of high biodiversity and richness during the Middle/Late Triassic, these tracemakers were very efficient bioturbators so that competition in the marine ecosystem increased during the Middle/Late Triassic. It is possible that the palaeogeographic position of the studied succession (at palaeolatitude 30°N to 35°N, Seyed-Emami 2003) were optimum for the occurrence of subtropical tracemaker suites (e.g., Bayet-Goll et al. 2015a). According to Goldring et al. (2004), tropical and subtropical zones are intensely bioturbated by a diverse endofauna including crustaceans.

7 Conclusions

The sedimentological and ichnological framework of the Late Triassic Nayband Formation in Central Iran has been used to generate a facies model that may be used to differentiate siliciclastic successions in non-deltaic shoreface and subaqueous delta settings. The trace fossil distribution and composition of ichnoassemblages is strongly linked with the inferred stability of physico-chemical conditions. Relying on the facies characteristics and stratal geometries, the siliciclastic succession is divided into two facies associations, FA (fluvial-dominated delta), and FB (open marine). The degree of river or wave-related influence becomes more clear when the intensity of bioturbation, trace fossil diversity, and relative size of individual ichnofossils are taken into account.

In deltaic successions, the trace-fossil suites indicate low diversities and low to moderate abundance of burrows,

poor development of tiering, and a sporadic distribution. The traces were made by trophic generalists and facies-crossing ichnogenera, and the impoverishment of suspension-feeding trophic types indicate a stressed, non-archetypal expression of the *Cruziana/Skolithos* ichnofacies. In contrast, the occurrence of diverse trace fossil suites attributable to the archetypal *Cruziana* ichnofacies and the *Skolithos* ichnofacies in wave-dominated shoreface-offshore environments points to stress-free environmental conditions in open marine settings. The facies scheme discussed here has the potential to improve the use of trace fossils and ichnofacies in palaeoenvironmental analysis, in particular for recognizing and differentiating deltaic successions from non-deltaic shoreline successions.

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